Domestic Preparedness: Sarin Vapor Challenge and Corn Oil Protection Factor (PF) Testing of 3M BE10 Powered Air Purifying Respirator (PAPR) with AP3 Cartridge

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Abstract. Results of performance testing of the 3M Model BE10 powered air-purifying respirator (PAPR) are described. Three series of tests were performed: (1) breakthrough time determinations of PAPR Cartridge Model AP3 against Sarin (GB) (2) GB vapor penetration determination of entire PAPR systems using manikin headform and simulated breathing, and (3) corn-oil protection factor determinations of PAPR systems using human subjects. Results indicate that cartridges provide adequate resistance to GB penetration against high-concentration challenges, but that corn oil aerosol and high-concentration GB vapor penetration into the breathing zone of the PAPR occurs at high levels, possibly through the hood-type head enclosure and/or the exhalation valve.

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Preface

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Table of Contents

1. Executive Summary

The 3M Model BE10 Powered Air-Purifying Respirator (PAPR) equipped with Cartridge Model AP3 was tested for resistance to penetration by chemical agent Sarin (GB) vapor and for the standard Army Protection Factor (PF) using human subjects and corn oil aerosols. The AP3 cartridges were also tested alone for resistance to GB vapor. The PAPR-GB test was performed by installing the PAPR on a headform connected to a breathing pump, enclosed in an exposure chamber into which a controlled concentration of GB vapor was introduced for the duration of the test. The cartridges were tested by preconditioning them in a controlled relative humidity, then installing them in test chambers where GB vapor-air was passed through the cartridges at a steady rate. The PF test was performed by having volunteers don PAPRs and enter a test chamber containing a uniformly distributed concentration of corn oil aerosol. The inside of the PAPR was connected by a sampling tube to a photometer that determined the concentration of aerosols inside the PAPR and compared it to the concentration in the chamber. The volunteers performed a series of exercises, and the concentration of aerosols in the PAPR was determined during each exercise. The ratio of aerosol concentrations in the chamber and inside the PAPR was used to calculate a PF during each exercise, and an overall PF was calculated. A distribution of the PFs for all volunteers was calculated. The results of the tests described were (1) none of the cartridges showed any penetration of GB; (2) each of the three systems tested showed penetration of GB, from the beginning of the test until the test was terminated and (3) the PF distribution indicated a pass percentage of 58% at the 10,000 PF level.

2. Introduction

Public Law 104-208 Omnibus Consolidated Appropriations Act, 1997, requested DoD to report to Congress on four specific issues: assess the types and characteristics of chemical and biological threats; identify unmet training, equipment, and other requirements for first responders; identify chemical/biological warfare information, expertise and equipment that could be adapted to civilian application; and present a detailed plan for DoD assistance in equipping, training, and providing other necessary assistance for first responders to such incidents. The Report to Congress: Domestic Preparedness Program in the Defense Against Weapons of Mass Destruction, (DP Program), authorized an Expert Assistance Personal Protective Equipment Evaluation Program. This program tasked the Edgewood Chemical and Biological Center (ECBC) of SBCCOM to perform testing of commercial Powered Air Purifying Respirator (PAPR) systems and cartridges, intended to be used by first responders.

The ECBC task force selected PAPRs for testing on the basis that the PAPR be NIOSH approved and provide protection against organic vapors and particulates, characteristics that are deemed necessary for protection against chemical agents and biological agents respectively. Six models of PAPR were selected and tested; the results

of these tests were reported previously. An additional PAPR, the 3M BE10, was selected later, and is the subject of this report.

Three series of tests were performed: GB agent vapor challenge of the filter cartridge, GB agent vapor challenge of the PAPR ensembles, and corn oil PF testing of the PAPR worn by volunteers.

A Powered Air Purifying Respirator is designed to supply clean filtered breathing air to a person's breathing zone, which may be enclosed in a partial or full facepiece or in a hood that covers the head. The blower is battery powered, and draws ambient air through one or more filters and discharges it via a tube into the wearer's breathing zone, at a rate of usually 170 L/min. It then flows out of the mask or hood from the bottom or an exhaust valve. Air that is breathed is expired into the air flowing through the respirator. GB is a nerve agent, an organophosphorus compound with a high volatility and therefore a respiratory hazard. The filter cartridge of a PAPR must be capable of adsorbing the GB vapor from the breathing air for the time that the PAPR will be worn; in these tests one hour was selected as the time the PAPR should resist penetration of the GB.

A glossary of terms used is included as Appendix A of this report.

3. Objectives and PAPR Description

The objectives of the task were threefold: to determine the resistance of the cartridge to GB vapor; to determine the protective potential of the PAPR ensemble against GB vapor; and to determine the protection factor for the PAPR.

The PAPR was 3M Model BE10, which has a butyl rubber hood with internal head harness, PVC visor , and exhalation valve on the visor. The breathing tube connection on the butyl hood is between the inner and outer cape; the inner cape is designed to be tucked inside the protective clothing. The inner cape also has an elastic drawstring to fit around the neck and head. Filtered breathing air from the Turbo Unit passes through the breathing tube and enters the rear of the hood, providing fresh air for the forehead and face. Air is expelled at the base of the hood. The Turbo Unit is powered with a rechargeable Nickel Cadmium Battery Pack which provides up to 8 hours of air for the system, at a rate of 170 L/min. The belt-mounted motor driven fan contained in an integral filter carrier draws ambient air through the filter media (three AP3 Cartridges) and supplies filtered air to the breathing tube and hood. This PAPR does not have a tight sealing surface around the face.

The AP3 cartridge uses activated carbon for the organic vapor sorbent material, and a High Efficiency Particulate Air (HEPA) filter to retain particulates. Biological agents, which are dispersed as particles, would be retained on a HEPA filter, and chemical agents, usually dispersed as organic vapors, would be adsorbed on carbon filters.

4. Chemical Agent Testing

a. Chemical Agent Testing Equipment.

(1) Vapor generator.

GB vapors were generated by using a syringe pump that injected liquid GB into a heated tee in the air dilution line. The rate of injection was such that the concentration was controlled to that specified in the test plan. The GB vaporized in the heated tee, was carried by the dilution air into the mixing chamber, thence into the exposure chamber. A Hydrogen-Flame Emission Detector (HYFED) was used to monitor the concentration in the exposure chamber during the test. For testing cartridges, liquid GB was contained in a glass 2-liter reservoir maintained at constant temperature. A metered stream of dry air passed into the reservoir to sparge vapors into a dilution air stream and mixing chamber. The mixture then passed into a test chamber containing the cartridge being tested.

(2) PAPR Test chamber.

The test chamber for the PAPRs was a Plexiglas® box of approximately 200 liters volume, with removable front panel, and four legs to allow air to flow through the fume hood under the chamber. A headform (SMARTMAN™) onto which the PAPRs were mounted for testing was attached to the floor of the chamber. A tube from the mouth area of the headform passed down through the head form and connected to a breather pump. A small tube connected the eye area to a remotely located Laboratory MINICAMS®. A port was provided in the wall of the chamber to introduce makeup air (vapor challenge). The outlet port was connected to military M12A1 scrubber filters. A small port connected to a Magnehelic Gauge to measure the pressure inside the chamber.

(3) Cartridge Test Chamber.

The test chamber for the cartridges was fabricated of stainless steel, cylindrical form, with one end removable. The removable end had a NATO thread adapter inside onto which the cartridges were fixed to be enclosed inside the test chamber for challenge with GB vapor. The outlet of the chamber was connected via a scrubber filter and rotameter to a vacuum source that generated a constant flow through the cartridge. A MINICAMS® was connected to the tubing between the outlet port and the scrubber filter to detect any breakthrough of GB.

(4) Breather pump.

The Military Breather Pump E1R1 (Jaeco Fluid Systems, Inc., Exton, PA) was used to simulate breathing through the PAPRs. This is a reciprocating pump that produces a sinusoidal breathing pattern (shaped like a half sine wave) by means of a gear system and a Scotch Yoke. The flow rate begins at zero, rises to a peak flow and falls back to zero with each piston stroke. The two flow characteristics that are of primary importance in filter testing are the minute flow or average flow in liters per minute, and

the peak flow, or maximum flow, which is approximately π times the minute flow for sinusoidal flow. Penetration of a filter, especially thin-bed filters, occurs sooner during sinusoidal flow than constant flow, because the challenge gas is distributed along the adsorbent layer exponentially with distance and penetration will occur well before the adsorbent layers at the inlet become saturated. The minute volume of this pump can be adjusted up to a maximum of 52 liters per minute, and the strokes per minute (breaths) can be adjusted. The peak flow of the pump is about 78 liters per minute when the breaths per minute is 25, at one liter per breath.

b. *Chemical Agent Testing Methods.*

(1) PAPR.

The PAPR system was subjected to a dynamic test wherein the hood was donned on a manikin headform, SMARTMAN, that was connected to the breather pump in the mouth area. The Turbo Unit, with cartridges attached, was powered to supply filtered air into the hood. The entire setup was enclosed in an exposure chamber of approximately 200-liter volume. The breather pump pulled air from inside the hood and discharged it back into the hood, where it was discharged through the exhalation valve and under the cape of the hood. The MINICAMS® was connected to a sampling port in the eye area of the SMARTMAN, such that it sampled air supplied by the Turbo Unit into the hood. The Turbo Unit passed air through the PAPR at 170 liters per minute. Makeup GB vapor-air mixture of 300 mg/m^3 concentration was supplied to the exposure chamber at 90 L/min; the resultant challenge concentration was 158 mg/m^3. The test was conducted for a total of 60 minutes. Three PAPRs were tested. The MINICAMS analyzed a sample of air from inside the hood every three minutes (See Table 1).

Table 1. Conditions For Testing PAPR Systems

Volume of makeup challenge concentration	90 L/min
Concentration of challenge GB	158 mg/ m^3
Breakthrough concentration limit	0.0001 mg/m^3
Total test time if break-through is not observed	60 minutes
Precondition of cartridges	25°C/50%RH,6 hrs
Temperature of test chamber	25±3°C
Flow of air through PAPR blower	170 L/min
Average flow of breather pump	25 L/min

(2) Cartridges.

The cartridges were tested individually by installing them in a test cell, generating a challenge GB concentration of 300 mg/m^3, and passing the challenge air through the cartridges at 28 L/min, constant flow, for 60 minutes (See Table 2). A MINICAMS was used to determine penetration of GB through the cartridge.

Table 2. Conditions for Testing Cartridges

Volume flow rate of challenge concentration	28 L/min
Concentration of challenge GB	300 mg/m^3
Breakthrough concentration detection limit	0.0001 mg/m^3
Total test time if breakthrough is not observed	60 minutes
Precondition of cartridges	25°C/50%RH, 6hrs
Temperature of test chamber	25±3°C
Relative Humidity of test air	50±5%

c. Chemical Agent Test Results and Discussion

(1) PAPR System Tests

Figure 1, Figure 2, and Figure 3 illustrate the GB vapor concentrations at the SMARTMAN sampling port during the 60 minutes of system tests 1, 2, and 3, respectively. These were tests of the three BE10 PAPRs mounted on the SMARTMAN headform. Each of the three systems showed penetration of GB, from the beginning of the test until the test was terminated at the end of one hour. The test results were not uniform; the first test reached a maximum GB concentration inside the hood of about 13 mg/m^3; the second test reached a maximum of 0.4 mg/m^3; the third test reached a maximum of nearly 120 mg/m^3.

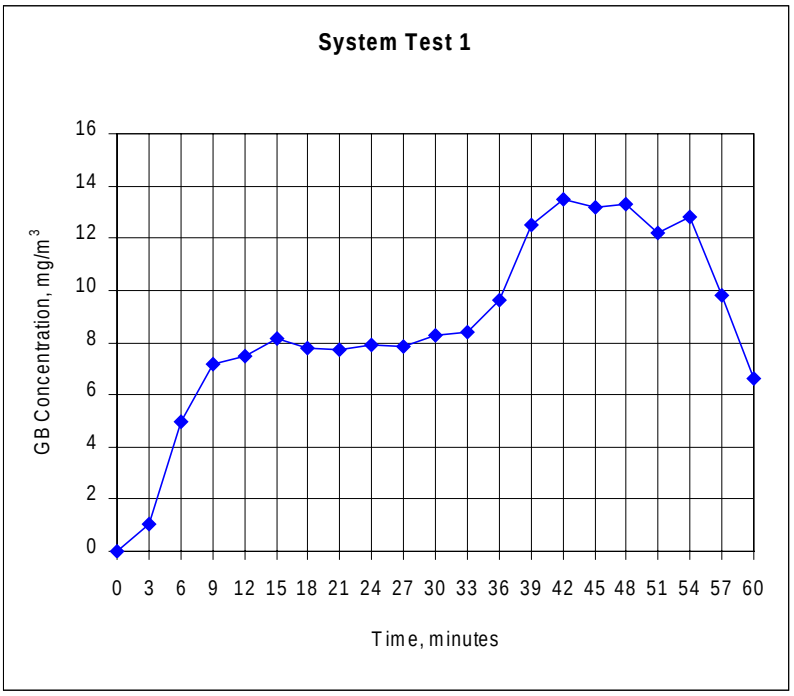

Figure 1. Concentration vs. Time for System Test 1

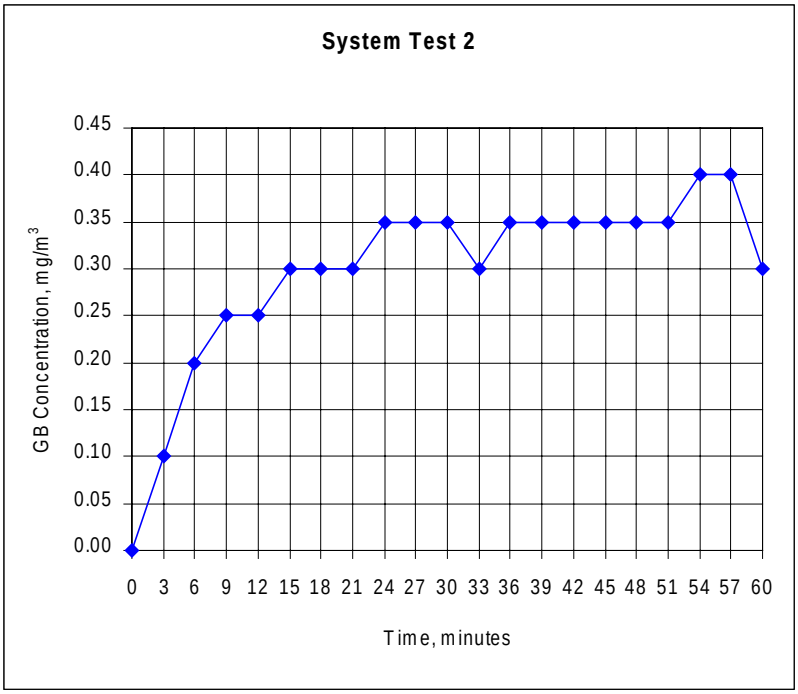

Figure 2. Concentration vs. Time for System Test 2

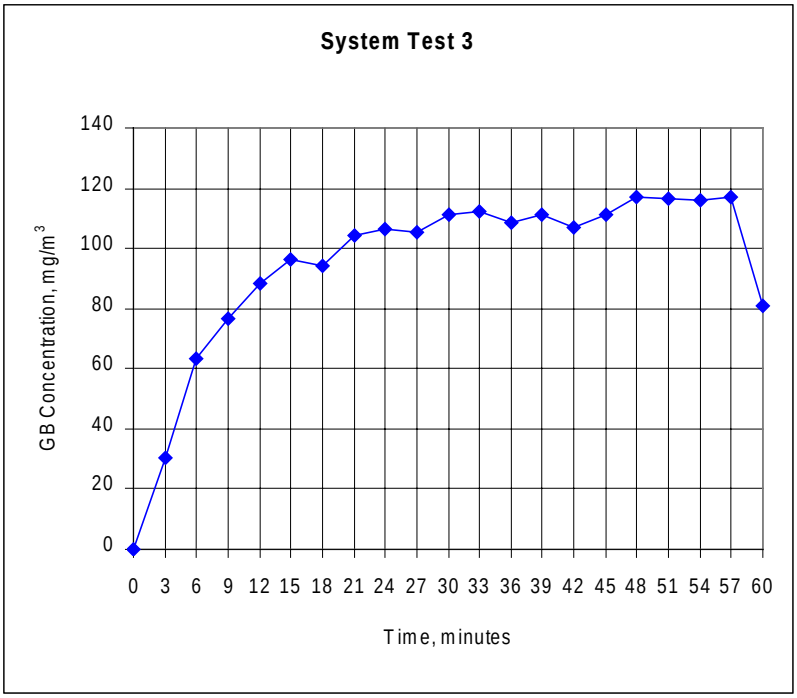

Figure 3. Concentration vs. Time for System Test 3

(2) Cartridge Tests.

A total of 22 cartridges were tested against GB. This number was selected because it represents 90% reliability at 90% confidence level when no failure occurs amongst the 22 items. One cartridge was tested for 6 hours, the remaining 21 were tested for one hour. None of the cartridges, including the one tested for 6 hours, showed any penetration of GB.

(3) Discussion.

Because none of the cartridge tests showed any GB penetration, it is unlikely that the GB detected inside the PAPR during the system tests penetrated the cartridges attached to the Turbo Unit. A possible source of penetration is the exhalation valve that is located on the front of the visor. The exhalation valve has a valve cover with a downward pointing snout. Air is supplied by the Turbo Unit at a constant rate of 170 L/min (with fully charged battery pack); the flow is through a breathing tube to the back of the head and down across the face, then it discharges under the bottom of the hood cape. Because of the high volume of air flow through the hood, the exhalation valve will be activated and a portion of the air will flow continuously out through the valve and cover. This flow through the valve cover could possibly cause turbulent flow that could entrain agent vapor from outside and discharge it inside the hood, particularly when the breather pump is operating to inhale and exhale air from the air supply, causing additional turbulent flow. Agent that is pulled inside will be detected. Figures 1, 2, and 3 indicate that GB was detected inside the hood from the beginning of the test. That the maximum concentrations of the three tests vary widely may be an indication that the turbulence is uncontrolled and that the leakage of agent inside the hood cannot be predicted.

5. Protection Factor Testing

a. Corn Oil Test Facilities.

A challenge aerosol concentration of approximately 20-40 mg/m^3, polydispersed corn oil aerosol having a mass median aerodynamic diameter (MMAD) of 0.4-0.6 microns (the Army Standard), was generated in a 10-ft $\times$ 10-ft $\times$ 32-ft test chamber. The test chamber challenge aerosol was generated by atomizing liquid corn oil at room temperature using a Laskin nozzle. The Laskin nozzle produced a coarse aerosol cloud, which was directed into an impaction plate to remove the larger particles and yield an aerosol in the desired size range. The concentrated aerosol from the generator was diluted with filtered ambient air to control the challenge aerosol concentration in the exposure chamber.

A 6-decade, 45 degree off-axis light-scattering laser photometer, sampling at a flow rate of 1-2 L/min, was used to quantify concentration of the challenge and the in-mask corn oil aerosols. For a given particle size, the quantity of scattered light is

proportional to the aerosol concentration. The photometer converted the quantity of scattered light to a voltage, which was then digitized and recorded by a microcomputer.

The PAPR sampling port was connected to the photometer with flexible silicone tubing to measure the amount of aerosol penetrating the mask. A Tygon® sampling tube line was connected from the exposure chamber sampling port to the photometer to determine the challenge aerosol concentration.

b. Protection Factor Test Methodology

The PAPR mentioned above was challenged with a corn oil aerosol over a one-week period with military volunteers. A total of 24 different volunteers were used in the test. Prior to testing, each test volunteer was given an orientation in which the PF test was explained by ECBC personnel and a volunteer agreement was signed by each test volunteer. A total of 48 trials were conducted, all with the PAPR "blown," i.e., operating with positive pressure.

All volunteers had anthropometric data taken of their facial features, and then they were given a PAPR and asked to wear their normal clothing (Battle Dress Uniform (BDU)). The test volunteers were then led into the aerosol exposure chamber, 8 at a time, by ECBC personnel, hooked up to their photometer stations, and asked to perform a standard Army PF Test devised to stress the face seal of the PAPR. In the test, volunteers were asked to perform the following ten exercises for one-minute each:

1. Normal Breathing
2. Deep Breathing
3. Turn Head Side to Side
4. Move Head Up and Down
5. Recite the Rainbow Passage (Reading a paragraph aloud to stress talking)
6. Sight the Rifle
7. Reach for the Floor and Ceiling
8. On Hands and Knees, Turn Head Side to Side
9. Facial Expressions
10. Normal Breathing

The test equipment operator monitored and communicated with the test volunteers on when to start an exercise, finish an exercise, and exit the aerosol chamber, and monitored their performance. All exercises were completed by the test volunteers without the intervention of test personnel.

All raw data were collected by a computer-based system and stored on a flexible diskette for later analysis.

c. Protection Factor Test Results And Discussion

Analysis of the data was completed for the NIOSH approved PAPR model using pass/fail percentages at selected PF levels. The PAPR was tested in the blown mode. Unblown mode was not tested for this PAPR because it did not have a tight sealing surface around the face. If the battery were to fail in a chemical environment, this PAPR would provide very minimal protection.

In this PF test, each test subject (24 subjects) performed the standard ten exercise routine twice in the blown mode for a total of 48 trials for this PAPR model. Where fewer occasions are reported it is because the test data were invalidated for some reason unrelated to the PAPR design. Because this was a commercially available PAPR there were no Army requirements established for this respirator. Therefore, we took the conservative approach and reported the data in pass and fail percentages for this PAPR configuration at selected PF levels. The analyzed data are provided in Table 3 for blown mode.

These PF tests were performed to provide useful information to federal, state and local emergency and hazardous materials (HAZMAT) teams operating in a chemical agent environment. A conservative approach was taken: the data were reported in pass and fail percentages. The pass percentages included in the summary tables are based on U.S. Army requirements (available upon request).

Table 3 shows that the PAPR (blown mode) had a pass percentage of 58% at the 10,000 PF level. This PAPR (blown mode) also had a pass percentage of 69% at the 6667 PF level and 85% at the 1667 PF level, respectively.

Table 3. Final PF Results, 3M BE10 PAPR

	3M PAPR (Blown)		
PF Range	*No. of Occasions in Range*	*Cumulative Rate, Percent*	*Cumulative Pass Rate, Percent*
10-49	0	0	100
50-99	0	0	100
100-499	4	8.3	92
500-999	2	12.5	88
1000-1666	1	14.6	85
1667-1999	2	18.8	81
2000-4999	4	27.1	73
5000-6666	2	31.3	69
6667-9999	5	41.7	58
10000-19999	9	60.4	40
20000-49999	5	70.8	29
50000-99999	9	89.6	10
100000(+)	5	100	0
No. of Trials	48		

(1) Data Analysis

Mask performance was quantified in terms of a protection factor (PF). The PF was calculated by determining the ratio of the challenge aerosol concentration to the in-mask aerosol concentration as quantified by integrating the peak voltage output from the photometer over the time interval. A PF was calculated for individual exercises (PF_i). The individual PFs were then used to calculate an overall PF for a subject (PF_o) as follows:

$$PF_o = n(\sum_{I\text{-}1 \text{ to } n} 1/PF_i)^{-1}$$

where n is the number of exercises. The overall PF provides a time-integrated measure of the protection afforded. It is somewhat analogous to calculating the total resistance of resistors in parallel in an electronic circuit. The PF_0 is affected most by the smallest PFs. Under the conditions of this test and the sensitivity of the photometer, the maximum PF that can be reported is 100,000. The PFs were calculated by a computer and stored to disk.

(2) Interpreting PF Summary Sheets

Overall PF is calculated by taking the inverse of the individual Protection Factors for each exercise, summing the values and finding the average. The inverse of this average is the overall PF.

The test data are summarized in Table 3. The first column lists the lower limit of each range of PF computed. The second column is the number of test occasions which resulted in calculated PF within the range. The third column presents the total number of test occasions which resulted in a PF below the lower limit of the range, presented as a percentage of the sample population. The fourth column is like the third, but presents the percentage which are above the lower limit of the range shown. The final PF range shown is over 100,000, but the current data acquisition system cannot measure PF over 100,000, so it truncates the data and puts all the remaining occasions in the final range.

6. Conclusions

A total of 22 cartridges were tested against a concentration challenge of 300 mg/m^3 of Sarin (GB). One cartridge was tested for 6 hours; the remaining 21 were tested for one hour. None of the cartridges, including the one tested for 6 hours, showed any penetration of GB.

Three BE10 PAPRs mounted on the SMARTMAN headform were tested against a concentration challenge of 158 mg/m^3 of GB. Each of the three systems showed penetration of GB, from the beginning of the test until the test was terminated at the end of one hour. The test results were not uniform; the first test reached a maximum GB concentration inside the hood of about 13 mg/m^3; the second test reached a maximum of 0.4 mg/m^3; the third test reached a maximum of nearly 120 mg/m^3.

PF testing was performed wearing the PAPR in the blown mode for a total of 48

trials in accordance with the U.S. Army PF testing standard (available upon request) for positive and negative pressure respirators used in a chemical-biological environment. The BE10 PAPR had a pass percentage of 58% at the 10,000 PF level, 69% at the 6667 PF level, and 85% at the 1667 PF level in the blown mode. No testing was performed in the unblown mode.

Appendix A

Glossary

Breather Pump

A pump used to simulate human breathing through a filter. The pump is a piston pump designed to begin the stroke at zero flow, rise to a maximum (peak) flow at midstroke, and decrease to zero at the end of the stroke. The resultant flow is sinusoidal, that is, shaped like a sine wave when plotted. The pump stroke can be adjusted to change the volume of air per stroke over a finite range; some pumps are capable of changing the number of strokes per minute.

Protection Factor (PF)

A Protection Factor is a number that is the direct result of a quantitative respirator fit test. It is a measurement made by an instrument during a simulation of workplace activities or scenarios. It is expressed as the challenge aerosol concentration outside the respirator divided by the challenge aerosol concentration that leaks inside the respirator during a fit test.

Hydrogen-Flame Emission Detector (HYFED)

A detector in which organophosphorus chemical compounds are burned in a hydrogen flame. Phosphorus compounds are formed that emit electromagnetic radiation whose wavelengths can be isolated and quantified.

MINICAMS®

Trade name for a chemical agent detector in which the agent is adsorbed from a specified volume of air onto an adsorbent tube which is then desorbed into the injection port of a gas chromatograph for analysis (quantitation). The acronym stands for "Miniature Continuous Air Monitoring System."

PAPR

Powered Air–Purifying Respirator with a tight or loose fitting facepiece with some kind of hose connected to a turbo unit or blower. The blower produces 4-6 cubic feet per minute of filtered airflow into the facepiece.

Sarin

An organophosphorus nerve agent, known by the military symbol GB. The chemical name is isopropyl methylphosphonofluoridate. GB reacts with the enzyme cholinesterase, thus interfering with the transmission of nerve impulses.